POWER-SYSTEM-WIDE ANALYSIS OF THE BENEFITS OF RESERVE PROVISION FROM SOLAR PHOTOVOLTAICS IN SOUTH AFRICA

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ABSTRACT: Reserve provision from standalone solar photovoltaic (PV) power plants has to date not been adopted in practice but has been conceptualised by a number of authors for variable renewable energy (RE) power plants like solar PV and wind. The authors have assessed the economic viability of this application in a developing country with low-levels of solar PV penetration thusfar (South Africa). The majority of power generation in South Africa is coal-fired, making up over 70% of the installed capacity. However, South Africa has abundant solar resources and has seen a dramatic decline in solar PV tariffs over the past few years. The value of reserve provision to the system from solar PV was determined by simulating the South African power system on an hourly basis in a least-cost unit commitment and dispatch model capable of co-optimising energy and reserves simultaneously. Preliminary results showed that purely reserve provision in the short term by new solar PV in South Africa is not yet economically viable as it requires a solar PV LCOE below 285 ZAR/MWh which is not likely to materialise in the short term.. However, results showed that a combination of reserve provision and energy generation by new solar PV capacity could be economically viable in the short term at solar PV LCOE below 430 ZAR/MWh. This research work is ongoing and will be expanded to include aspects of solar PV forecasting, investigations into the provision of other reserve types by solar PV simultaneously, reserve provision by other Renewable Energy (RE) technologies as well as further research into possible reserve costing and incentivisation.

Keywords: Large grid-connected PV systems, simulation, co-optimisation, cost reduction, developing countries, economic analysis, grid integration, reserves

1 INTRODUCTION

Reserve provision from standalone solar photovoltaic (PV) power plants has to date not been adopted in practice but has been conceptualised by a number of authors for variable renewable energy (RE) power plants like solar PV and wind [1]–[4]. The authors have assessed the economic viability of this application in a developing country with low-levels of solar PV penetration thusfar (South Africa). This is envisaged to create a new business case, prepare for better grid integration as well as increasing the viability of high solar PV penetration levels in future.

A brief background of the South African context, the requirement for reserves in a power system and reserve provision by solar PV is provided. This is followed by the approach taken to determine the economic viability of reserve provision by solar PV, the presentation of selected results, a brief discussion of the saliency of these results, suggested future research work and conclusions.

2 BACKGROUND

2.1 The South African context

The current South African power system is summarised in Table 1. It is predominantly coal based with small amounts of nuclear, hydro and pumped storage generation capacity. Only since 2014 has utility scale RE been deployed via the Renewable Energy Independant Power Producer Procurement Programme (REIPPPP) [5]. This has included solar PV, wind, Concentrated Solar Power (CSP), biomass, biogas and small hydro renewable energy (RE) technologies.

The REIPPPP has resulted in significant tariff reductions for solar PV in South Africa (Figure 1) to the point where planning assumptions for expected 2030 solar PV tariffs had already been reached in 2014 (reductions from 3500 ZAR/MWh to 840 ZAR/MWh in 3 years, annual average exchange rates in 2015 were EUR:ZAR: 14.2 and USD:ZAR: 12.8).

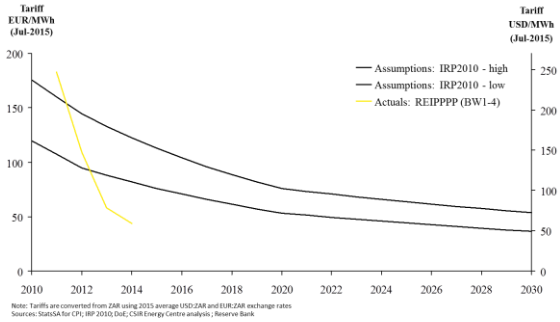

Figure 1: Actual solar PV tariffs in South Africa for bid-windows 1-4 of the REIPPPP

Electricity plans for South Africa (Figure 3) currently indicate that from the small base of 1 GW in 2015, solar PV is planned to expand to 8.4 GW of installed capacity by 2030 (~10% of total installed capacity) while providing ~2.8% of total energy [6]. However, indications in updated plans not promulgated (Figure 4) have been that solar PV could contribute 9.8 GW by 2030 and 25 GW by 2050 while contributing 4.9% and 9.6% of annual energy respectively [7].

Work in [8] showed that solar PV potential in just high density settlement areas of South Africa (rooftop solar PV) is ~73 GW and that there is ~220 GW of utility scale solar PV just in existing Environmental Impact Assessment Areas (EIAs) i.e. total of ~300 GW of easily accessible solar PV capacity.

The solar resource in South Africa is almost twice that of Germany (Figure 2). As shown in Table 1, Germany already have an installed solar PV capacity of ~40 GW [9]. South Africa currently only have ~1 GW of installed solar PV capacity.

Globally, solar PV installed capacity at the end of 2015 totalled 227 GW. This is dominated by China (45 GW), Germany (39 GW), Japan (35 GW), the United States (27 GW) and Italy (19 GW). In 2015, 50 GW of solar PV capacity was installed (mostly by China, Japan, the United States and United Kingdom) [10].

Considering the significant solar resource in South Africa, significant tariff reductions in the REIPPPP and solar PV adoption globally, the planned share for solar PV in South Africa's power system is not very ambitious and should likely be higher. Thus, the value of solar PV providing reserves (in addition to energy) is likely to be a beneficial research effort in demonstrating additional value to the power system.

Table 1: Summary of current South African and German power systems (2015)

Property	*Unit*	*RSA*	*DE*
Demand	[TWh]	~240	521
Peak demand	[GW]	34.1	83.1
Installed capacity	[GW]	54	193
Coal	[GW]	38	49
Gas/oil	[GW]	4	33
Nuclear	[GW]	2	11
Hydro (incl PS)	[GW]	5	6
Wind	[GW]	1	46
Solar PV	[GW]	1	39
CSP	[GW]	<1	-
Other	[GW]	<1	9

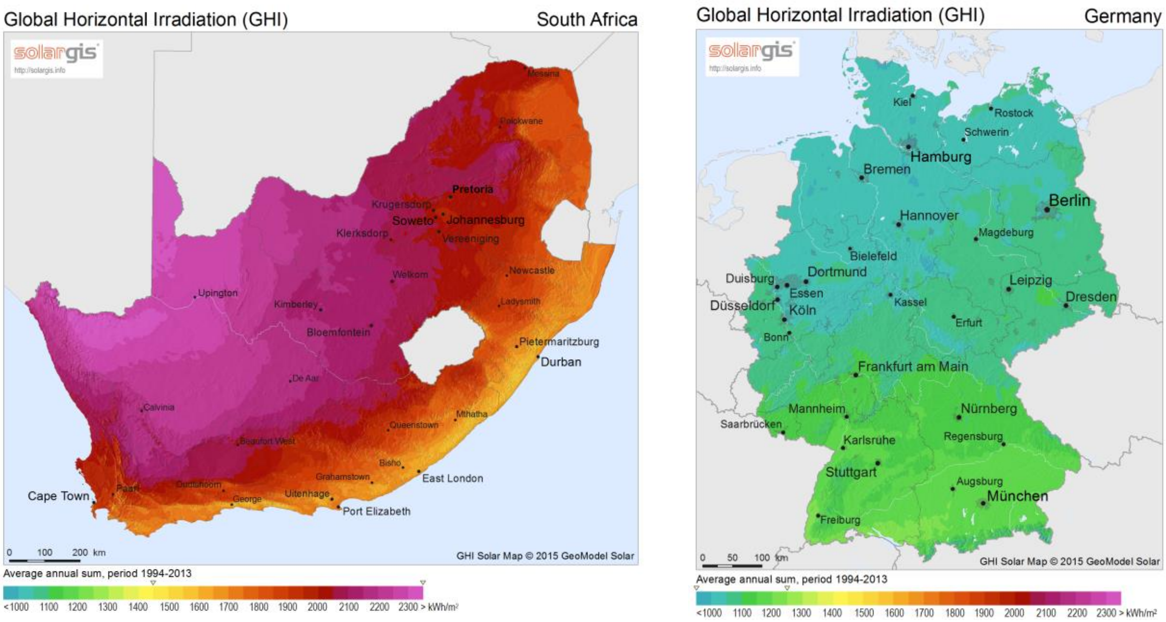

Figure 2: South Africa and Germany average annual GHI (1994-2013) [8]

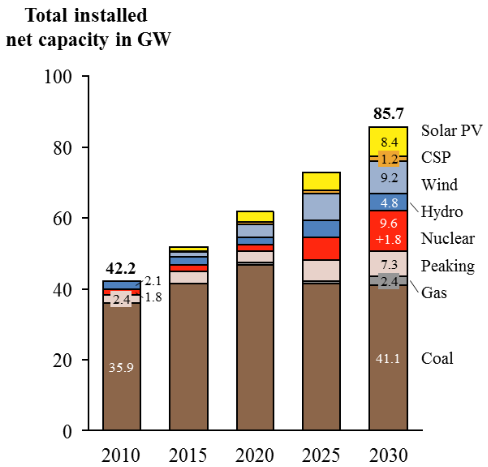

Figure 3: Power system expansion plans to 2030 in South Africa

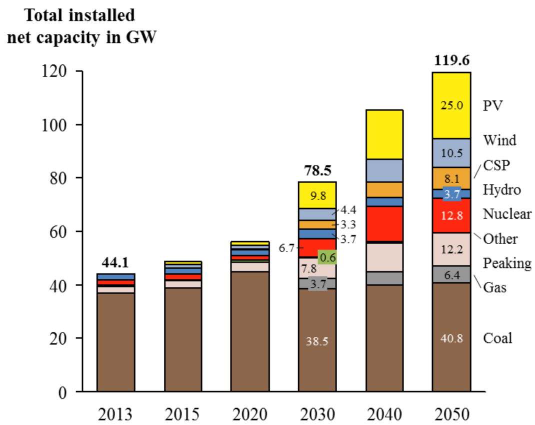

Figure 4: Updated power system expansion plans to 2050 in South Africa (not promulgated)

2.2 The requirement for reserves

The main task of any System Operator (SO) is to continuously balance electricity supply and demand in the power system. If supply and demand are not balanced at any particular time, the system frequency will deviate from the scheduled frequency (50 Hz or 60 Hz, country dependant). Significant frequency deviation could lead to damage of generators, transmission infrastructure, end-user equipment, result in under-frequency or over-frequency load shedding and possibly system collapse if insufficient action is taken. It is impossible for any SO to maintain system frequency at the exact scheduled frequency at all times as a result of uncertainties in demand forecasts and generation/ transmission availability. SOs also do not typically own generation infrastructure and as a result, it is generally accepted that the SO will maintain system frequency within a reasonable range by procuring a certain amount and type of reserves to ensure a balanced system. The nature of the three types of reserves most commonly applied and the system frequency are shown illustratively in Figure 5 (following a large disturbance i.e. a loss of supply). A similar graphic but with the inverse response from reserves (down) would represent a loss of system demand.

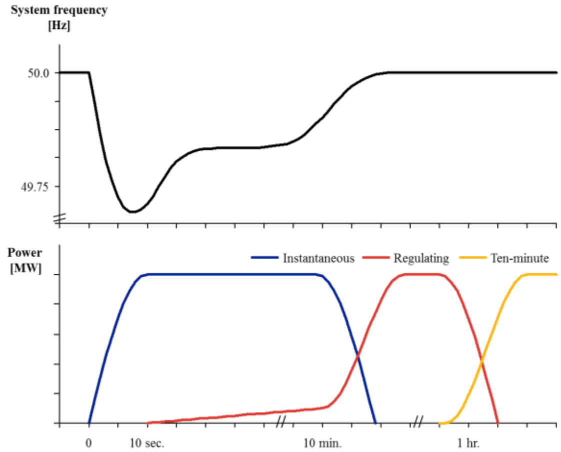

Figure 5: Illustration of system frequency and reserve response following a large system disturbance i.e. loss of supply (adjusted from [11])

Currently in South Africa, the five reserve types procured are summarised in Table 2 [12]. Operational reserves include Instantaneous (Up/Down), Regulation (Up/Down), Ten-minute and Emergency reserves (Supplemental reserves are not considered part of operating reserves). Emergency and Supplemental reserves are used very infrequenctly with the former only being used when the power system is in an abnormal state.

The provision of operating reserves in South Africa is mainly by coal-fired thermal power stations with smaller amounts being provided by pumped storage capacity and Open Cycle Gas Turbines (OCGTs). The drawbacks of the majority of reserves being provided by coal-fired generators are having to operate at part-load (reducing efficiency) as well as this relatively cheap generation fleet not being able to produce as much energy as possible.

Table 2: Reserve types and characteristics in South Africa

Type	*Response [min]*	*Full activation [min]*	*Sustain [min]*
Inst. Up/Down	-	10 sec.	10
Reg. Up/Down	10 sec.	10	60
Ten-minute	<10	10	120
Emergency	10-30	<30	120
Supplemental	<360	360	120

2.3 Reserve provision by solar PV

Solar PV plants can technically provide any reserve type as a result of their near instantaneous response time. Down reserves provision would be provided by the curtailment of solar PV from maximum available output while up reserves would be provided via constant curtailment and increase of output to maximum available output when activated by the SO. The primary technical constraints in this regard are:

i. Solar PV plants are operating at above zero levels i.e. it is day time.
ii. Size and geographic distribution of plants is large enough to allow for aggregation that sufficiently reduces uncertainty
iii. Contract duration of the reserve product is not too long (again, to reduce uncertainty)

Providing down reserves is feasible as it is merely the typical curtailment of solar PV production when required i.e. unless activated by the SO, there will be no effect on solar PV production. Providing up reserves would entail constant curtailment of production until activated by the SO and is thus more difficult to justify.

This study is focused only on the provision of Instantaneous Up reserves provided by solar PV plants in South Africa.

3. APPROACH AND ASSUMPTIONS

The value of reserve provision to the system from solar PV was determined by simulating the South African power system on an hourly basis in weekly steps in a least-cost unit commitment and dispatch model capable of co-optimising energy and reserves simultaneously. The simulation was only conducted to represent the short term (<5 years) with no new supply capacity assumed other than supply capacity already under construction.

Existing generator properties were modelled with publically available data and generally accepted technical assumptions were made where public data was not available. Hourly solar PV profiles for South Africa were obtained from [13] and scaled with installed capacity.

The system was modelled and total system production costs determined without any additional solar PV capacity. Following this, a pre-defined amount of solar PV capacity was added (which could provide either energy or reserves) and total system production costs were determined. This simulates the decision being considered; should a solar PV plant be built for reserve and/or energy provision in South Africa? The value added to the system with the provision of energy or reserves by the new solar PV capacity is then calculated as the total production cost difference between these two cases. The economic viability of solar PV providing reserves will be when the value provided to the system is greater than solar PV Levelised Cost of Electricity (LCOE).

System production costs include fuel costs, variable operation and maintenence (O&M) costs as well as unit start and and stop costs. All costs are in July 2015 South African rands (ZAR).

All operating reserve types were modelled as being mutually exclusive to align with [14], as shown in Table 2 and Table 3.

In three cases of new solar PV capacity being considered solar PV is assumed to be:

i. 500 MW installed capacity with no Instantaneous Up reserve provision (all energy)
ii. 500 MW of Instantaneous Up reserve provision at any time it is available
iii. 500 MW of Instantaneous Up reserve only between 10h00-15h00 daily.

The three demand scenarios considered to represent different demand growth scenarios in the short term are taken from [15] and shown in Table 4.

Table 3: South African reserve types and provision modelled

Type	*Risk, Summer peak [MW]*	*Risk, Winter peak [MW]*	*Risk, Summer off-peak [MW]*	*Risk, Winter off-peak [MW]*
Inst. Up/Down	500	500	800	800
Reg. Up/Down	500	600	500	600
Ten-minute	1200	1100	900	800

4. RESULTS AND DISCUSSION

For the demand scenarios assessed, the value of solar PV Instantaneous Up reserve provision is summarised in Table 4 and graphically in Figure 6. The simulation results showed that when the system is more constrained (higher demand scenario), there is more value provided by solar PV for both energy and reserve provision. In addition, solar PV provides more value to the system when generating than providing reserves for all demand scenarios. This ranged from 350-675 ZAR/MWh when solar PV provides no reserve (only generates) and 21-285 ZAR/MWh for 100% reserve provision. Thus, for 100% solar PV reserve provision to be economically viable, the LCOE would need to be less than 285 ZAR/MWh. For the case of a combination of solar PV energy production and reserve provision (35/65), the LCOE of solar PV would need to be at most 430 ZAR/MWh.

As can be seen, preliminary results showed that pure reserve provision in the short term by new solar PV capacity in South Africa is not yet economically viable as it requires a solar PV LCOE below 285 ZAR/MWh (not likely to materialise in the short term). However, results showed that a combination of reserve provision and energy generation by new solar PV capacity could be economically viable in the near future at solar PV LCOE below 430 ZAR/MWh.

Weekly patterns of the three reserve provision cases for solar PV is shown in Figure 7 to Figure 9. These three reserve provision cases provide 14%, 9% and 0% respectively of total Instantaneous Up reserves (of the required 6.54 TWh annually).

For illustration purposes, actual generation superimposed onto reserve provision (with available capacity) are shown for solar PV, thermal (coal-fired), pumped storage and OCGTs in Figure 10 to Figure 13 (for the case of solar PV reserve provision between 10h00-15h00 daily).

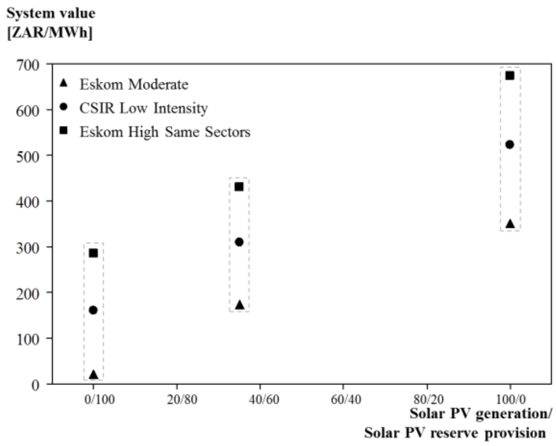

Figure 6: Range of system value provided for a range of generation to reserve provision ratios

5. FUTURE RESEARCH

The current research determined at what LCOE it is feasible for solar PV to provide reserves and/or energy. Future research will consider the case where solar PV capacity already exists and at what solar PV prices it is economically viable to provide varyinng levels of reserves.

Aspects of solar PV forecasting and the associated uncertainty which could impact the assumed amount of solar PV available for reserve provision in particular timeframes is not only critical for improved system operations but can be used to improve the business case for reserve provision by solar PV e.g. hour-ahead, day-ahead, week-ahead etc.

Investigations into the provision of other reserve types by solar PV simultaneously with Instantaneous Up reserves will be investigated. This will include Regulating and 10-Minute reserve types with up and down reserve considerations.

Similar to the research being undertaken on solar PV specifically, the provision of reserves by other RE technologies like wind and Concentrated Solar Power (CSP) are also under consideration. This will initially be considered independently (on a per technology basis) following which the integration of all RE technologies simultaneously will be pursued.

The incentive to provide reserves by any reserve provider will be driven inherently by policy and market structures. The associated incentives required are also under consideration with the specific context of South Africa in mind but generalisation to international jurisdictions with existing and planned high penetration of RE is being considered. As an example, reserve could be valued as the marginal cost to meet the next increment of reserve requirement in each interval at the optimal solution of the energy and reserves co-optimisation i.e. the shadow price of reserve provision in each interval.

optimising energy and reserves simultaneously.

6. CONCLUSIONS

The majority of power generation in South Africa is coal-fired, making up over 70% of the installed capacity. However, South Africa has abundant solar resources and has seen a dramatic decline in solar PV tariffs in recent years.

The value of reserve provision to the system from solar PV was determined by simulating the South African power system on an hourly basis in a least-cost unit commitment and dispatch model capable of co-optimising energy and reserves simultaneously.

Preliminary results showed that only reserve provision in the short term by new solar PV in South Africa is not yet economically viable as it requires a solar PV LCOE below 285 ZAR/MWh which is not likely to materialise in the short term.. However, results showed that a combination of reserve provision and energy generation by new solar PV capacity could be economically viable in the short term at solar PV LCOE below 430 ZAR/MWh.

Table 4: Summary of scenarios assessed for up to 500 MW solar PV reserve provision (Instantaneous Up)

Demand scenario	*Annual energy demand [TWh]*	*System peak demand [GW]*	*Annual reserve provision (total) [TWh]*	*Annual reserve provision (solar PV) [%]*	*Annual reserve provision (others) [%]*	*System value of solar PV [ZAR/MWh]*
Eskom Moderate	*256*	38.2	6.54	14	86	21
				9	91	174
				-	100	351
CSIR Low Intensity	*271*	40.4	6.54	14	86	161
				9	91	309
				-	100	522
Eskom High Same Sectors	*274*	41.0	6.54	14	86	285
				9	91	431
				-	100	674

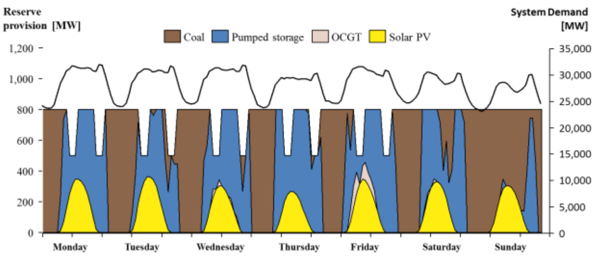

Figure 7: Sample week of reserve provision with solar PV as a reserve provider (Instantaneous Up)

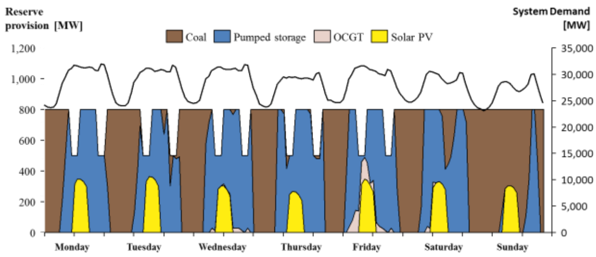

Figure 8: Sample week of reserve provision with solar PV as a reserve provider between 10h00-15h00 (Instantaneous Up)

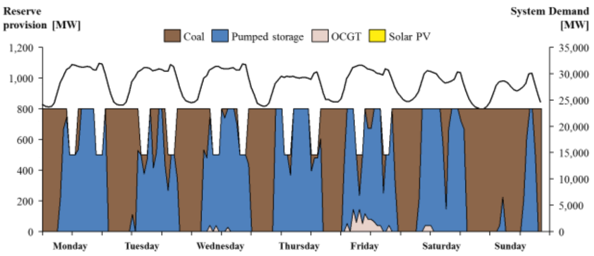

Figure 9: Sample week of reserve provision without solar PV as a reserve provider (Instantaneous Up)

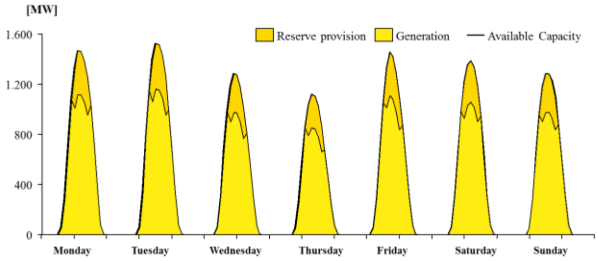

Figure 10: Sample week of solar PV reserve provision (Instantaneous Up), generation and available capacity

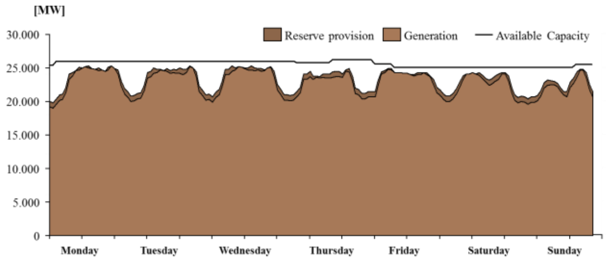

Figure 11: Sample week of thermal (coal fired) reserve provision (Instantaneous Up), generation and available capacity

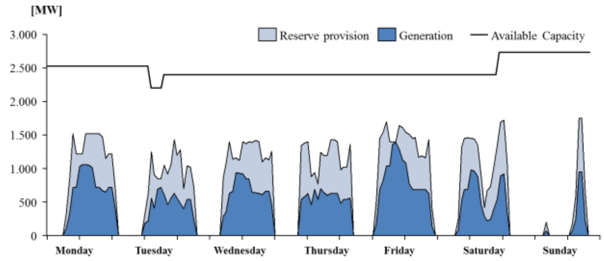

Figure 12: Sample week of pumped storage reserve provision (Instantaneous Up), generation and available capacity

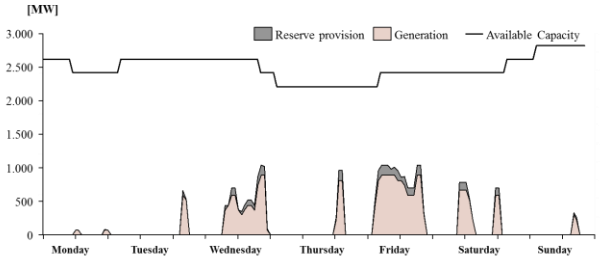

Figure 13: Sample week of OCGTs reserve provision (Instantaneous Up), generation and available capacity

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